

# Development of a Footwear Sizing System in the National Football League

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**Context:** Footwear performance and injury mitigation may be compromised if the footwear is not properly sized for an athlete. Additionally, poor fit may result in discomfort and foot injury such as fifth metatarsal stress fracture, foot deformities, turf toe, and blisters. Current footwear fitting methods consist of foot length and width measurements, which may not properly describe the shape of the individual foot, correlated with shoe size descriptors that are not standardized. Footwear manufacturers employ a range of sizing rubrics, which introduces shoe size and shape variability between and even within footwear companies. This article describes the synthesis of literature to inform the development and deployment of an objective footwear fitting system in the National Football League (NFL). The process may inform athletic footwear fitting at other levels of play and in other sports.

**Evidence Acquisition:** Literature related to footwear fitting, sizing, and foot scanning from 1980 through 2017 was compiled using electronic databases. Reference lists of articles were examined for additional relevant studies. Sixty-five sources are included in this descriptive review.

**Study Type:** Descriptive review.

**Level of Evidence:** Level 5.

**Results:** Current methods of footwear fitting and variability in the size and shape of athletic footwear complicate proper fitting of footwear to athletes. An objective measurement and recommendation system that can match the 3-dimensional shape of an athlete's foot to the internal shape of available shoe models can provide important guidance for footwear selection. One such system has been deployed in the NFL.

**Conclusion:** An objective footwear fitting system based on 3-dimensional shape matching of feet and shoes can facilitate the selection of footwear that properly fits an athlete's foot.

**Keywords:** footwear fitting; 3-dimensional foot scanning; footwear sizing system

The evolution of athletic footwear is driven by esthetics, comfort, and the incorporation of technologies within the shoe to protect athletes from injury and to optimize their performance.<sup>59</sup> Recently, it has been argued that athletic footwear should be classified as a piece of protective equipment<sup>23</sup> rather than simply performance equipment or apparel. Specific footwear parameters such as outsole traction and forefoot bending stiffness can influence athletic injury and performance,<sup>11,15,39,61</sup> but effectiveness may be reduced if the footwear is not properly sized for the athlete. Additionally, factors directly associated with poor footwear fit include player

discomfort,<sup>17</sup> foot injury such as fifth metatarsal stress fracture,<sup>46</sup> foot deformities,<sup>40</sup> turf toe, and blisters.<sup>13,20,29,53,55</sup>

Footwear manufacturers determine their own sizing rubrics, which introduces size and shape variability between models, even within footwear companies. This causes substantial differences in the internal measurements of shoes that are nominally the same size,<sup>24</sup> making fitting difficult. An unbiased sizing system that provides athletes with information regarding the fit of specific footwear (make, model, and size in that make and model) in relation to their own individual foot shape would facilitate footwear selection. Recently, such a system was

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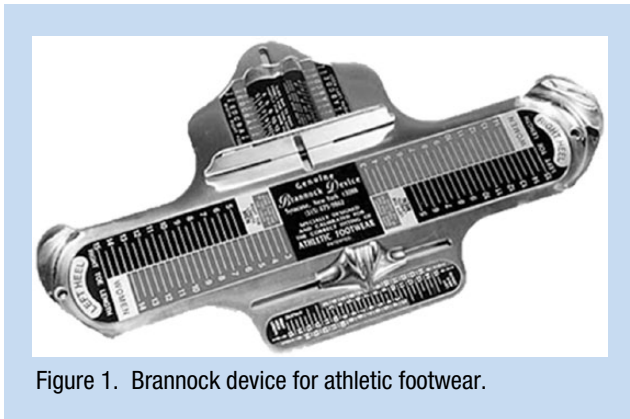


Figure 1. Brannock device for athletic footwear.

implemented within the National Football League (NFL). The aim of this article is to review current and advanced methods of footwear sizing, to provide an overview of the development and implementation of the footwear sizing recommendation system within the NFL, and to discuss how such a system may inform athletic footwear selection more broadly.

## THE FOOT

Athletically, the foot is frequently the only part of the body in contact with the ground and is required to exert force against the ground during athletic tasks such as running and jumping. During these tasks, the foot must perform a range of functions, and substantial alterations in the shape of the foot can occur.<sup>32,41</sup> The foot increases in size and changes shape when loaded and, for more than 80% of individuals, one foot will deform differently than the other when loaded.<sup>56</sup> Loading is not the only stimulus that will alter the shape of the foot, as foot volume has been shown to change up to 5% due to changes in foot temperature.<sup>56</sup> Additionally, factors such as age<sup>58</sup> and anatomical features linked to background and environment<sup>19,31</sup> can influence the dynamic shape of the foot. Even aspects of the shoe itself can alter foot shape, with shoe heel height altering foot breadth and arch length in a nonlinear manner.<sup>1,33</sup>

## CURRENT FOOTWEAR SIZING

An American Society for Testing and Materials (ASTM) standard exists for fitting athletic footwear.<sup>4</sup> The foot measurements described in the standard include foot length (from the heel to the tip of the longest toe), foot width (widest part of the foot), and arch length (distance of the first metatarsophalangeal [MTP] joint from the heel), with these measurements conventionally being measured with the Brannock measurement device that was patented in 1926<sup>42</sup> (Figure 1). These foot measurements provide a general description of the size of the foot, lack the resolution to characterize other dimensions that more fully characterize the overall shape of the foot, and may be important in the selection of a shoe model and size.

The current American standard shoe sizing system defines full sizes nominally by length increases of 1/3 of an inch (8.46 mm),

half sizes by 1/6 of an inch (4.23 mm), and widths (AAAA to EEE) with nominal step increases of 3/16 of an inch (4.76 mm).<sup>43</sup> Over the years, the footwear industry has adapted standardized sizing to their own metrics based on style, heel height, materials, type of construction, sole thickness, brand and manufacturer, intended use, and other priorities.<sup>56</sup> Differences in sizing have therefore evolved both between and within footwear companies.<sup>23,24</sup> Specific to the NFL, prior to the 2016 and 2017 football seasons, internal length and width measurements were taken of more than 50 different shoe models from 3 different brands, all labeled as size 12 US. The internal length of each shoe was measured from the most posterior point on the heel to the most anterior point in the toe box using a PlusMed12 device (Figure 2, left). The internal width was measured using a telescoping rod placed at 70% of the inside length of the shoe from the heel (Figure 2, right), which is presumed to be the approximate longitudinal location of the medial foot flexion axis.<sup>11</sup>

Length measurements in 2016 for nominal size US 12 models (Figure 3, top left) ranged from 287 to 302 mm. That 15-mm range corresponds to greater than a 1.5 US shoe size difference based on the historical sizing metrics described above.<sup>43</sup> Furthermore, the variability in length was not clearly correlated with brand, intended player positions, or player weight recommendation.

The widths of 2016 models were also highly variable across nominally size 12 shoes (Figure 3, bottom left), with a range of 93.5 to 105.5 mm. This 12-mm range represents almost 3 size steps in ball girth widths,<sup>43</sup> so it is not unreasonable that a population of shoes intended to represent “regular” and “wide” feet would exhibit a range of that magnitude. From a fitting perspective, however, shoes specifically labeled as “wide” by the footwear brands were generally not wider in terms of this width measurement than shoes that were “regular” width.

These measured lengths and widths were provided to the NFL and to 3 footwear brands, and the brands were encouraged to tighten their length specifications and improve their “wide” designation so that it corresponded to a measured width relative to a “regular” version of the same model. For the 2017 models, the difference in length across size 12 shoes decreased to 11 mm (just over 1 nominal size, length from 291 to 302 mm) (Figure 3, top right). The difference in width increased from model year 2016 to 2017 to 15 mm (92 to 107 mm) (Figure 3, bottom right) due to the development of wide versions of certain models that were available only as regular widths in 2016. Importantly, however, all footwear brands by 2017 had correctly labeled as “wide” the wider of models for which “regular” and “wide” versions were provided.

The variability in lengths and widths of shoes labeled the same size may require an athlete to try on multiple shoes and models. More important, misconceptions about size may lead an athlete to select a model and/or size that does not properly fit his foot. Though some improvements in dimensional tolerances and labeling have been achieved in NFL shoes, the need remains for an objective measurement and recommendation



Figure 2. Photographs of shoe length measurement using the PlusMed12 device (left) and width measurement using the telescoping rod at 70% of the footwear length from the heel (right).

system that can accommodate the full 3-dimensional (3D) shape of an athlete's foot and the extant shoe models from which he must choose.

### ADVANCED FOOTWEAR SIZING METHODS

To properly fit footwear, information regarding the footwear itself, specifically the internal dimensions and shape of the shoe or of the last used to make the shoe, is required in addition to the athlete's foot size and shape.<sup>9,47</sup> With quantitative shape information, methods may be applied to match the shape of the individual's feet to available footwear shapes. Several such methods have been proposed, with early methods comparing a 2-dimensional (2D), top-down outline of the foot to a 2D top-down outline of the outside bounds of the shoe.<sup>16,63,64</sup> If the foot is within the outline of the shoe, it will be loose, while if the

foot is outside, it will be tight.<sup>16</sup> Regions of the outline are given either a positive error, meaning the foot was inside the outline of the shoe, or a negative error, meaning the foot was outside the outline. For proper fit, positive error is needed in specific areas such as the instep and the toe region, while negative error is needed in other areas such as the heel to prevent foot slippage.<sup>37</sup> One difficulty in matching shoe shape to footwear shape is determining the thresholds for these errors. They are application specific and should be defined to ensure shoe performance and expected comfort under multiple scenarios. Additional complexity is introduced by variability in athletes' preferences regarding the locations and magnitudes of shoe tightness or looseness.

Modern methods of foot/shoe matching almost all use some form of 3D scanning to generate a model of the foot. Three-dimensional scanning of the human body as a technology is

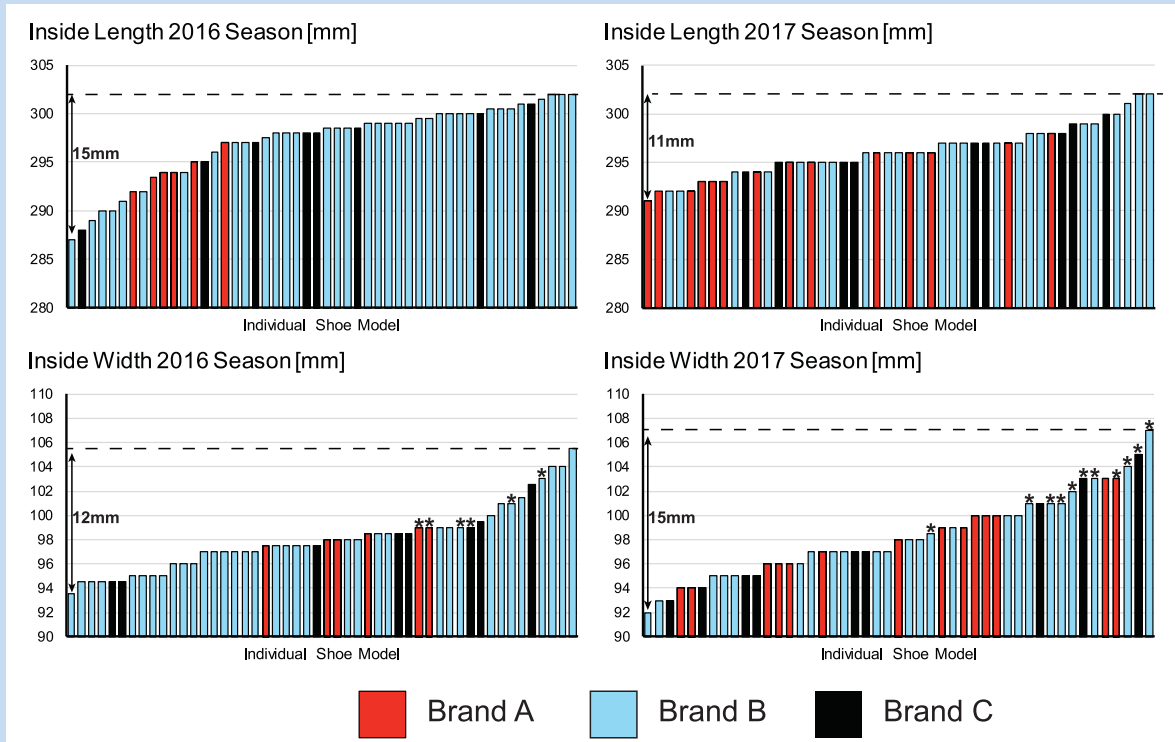


Figure 3. Inside length (top row) and inside width (bottom row) of different footwear models for the 2016 (left column) and 2017 (right column) seasons. Asterisks represent shoe models that were labeled as “wide” by the different footwear brands.

more than 25 years old,<sup>12</sup> but the past decade has seen significant improvements in scanners and the associated software at a reduced cost. Contemporary 3D scanning of the feet commonly uses 1 of 2 technologies: laser scanning<sup>7,57</sup> or structured light scanning<sup>57</sup> (see the Appendix, available in the online version of this article, for a description of each).

With these 3D foot scanning methodologies, conventional Brannock measurements and detailed foot shape data can be collected accurately and objectively in a matter of seconds. These measurements can then be used to estimate a nominal shoe size, but appropriate sizing for a particular footwear model remains limited by the lack of information on the internal dimensions of the candidate footwear. There currently is no standard method by which the internal measurements of footwear are determined. Methods for obtaining shoe information include physical measurements<sup>23</sup> and 3D scans of either an internal mold,<sup>52</sup> the shoe last,<sup>8,30,40,41,44,65</sup> or the inside of the shoe<sup>10,51,52</sup> (see the Appendix for further details).

After the collection of individual foot and footwear shape information, foot-to-shoe matching can occur. Different methods of varying complexity have been used. Some involve simply minimizing the error among specific foot and shoe measurements or between 3D shape outlines of the foot and shoe,<sup>37,41</sup> while more advanced classification algorithms have also been proposed. Examples include linear discriminant analysis, naïve Bayesian classification, k-nearest neighbors, or

support vector machine classification and statistical shape analysis.<sup>6,30,34,36-38,45,60</sup>

Variability in individual athlete preferences for comfort and perceived performance complicates this geometric matching regardless of the complexity of the method. Wearers' perception of comfort is particularly sensitive in the MTP and arch regions of the foot,<sup>5,35</sup> and perception of fit is particularly sensitive in the toe and ball area.<sup>40</sup> In general, if a shoe is too tight, it will be felt in the forefoot region, while if a shoe is too loose, it will be felt in the heel region.<sup>14</sup> Some individuals prefer tighter shoes in specific areas, while other individuals prefer looser shoes. Additionally, fitting tolerances and preferences are application specific, with individuals likely having different tolerances and preferences of fit for a walking shoe compared with a football cleat.

To determine different functional groups of foot shape and fit while accounting for different fit preferences, a large database of foot scan data of the sample population is generally obtained<sup>25,26,50</sup> in addition to subjective assessments of fit of a variety of different footwear.<sup>48,51</sup> In general, for subjective assessment of fit, many participants will try on multiple pairs of shoes and provide feedback on various aspects of the shoes such as overall and region-specific comfort (forefoot, midfoot, rearfoot) in addition to participants highlighting areas on the shoe that they feel are too tight or too loose.<sup>49</sup> This will assist in developing the tolerances for the specific population of interest. To further obtain information in terms of individual fit, prescan

questionnaires may be implemented to obtain personal preferences of fit and tightness/looseness. Similarly, when participants are selecting new footwear, a questionnaire based on the fit of their previous footwear may be implemented to obtain personal preferences of fit and familiarity to further optimize the shoe recommendation system.

## **PRACTICAL EXAMPLE: DEVELOPMENT AND DEPLOYMENT OF A FOOTWEAR FITTING SYSTEM WITHIN THE NFL**

Lower extremity injuries can be generated by loads passed through the shoe to the foot during elite-level football.<sup>3,21,22,27,28,54,62</sup> Several characteristics of the NFL create a unique environment for developing and implementing a footwear sizing system as part of an overall lower extremity injury prevention program. First, lower extremity injuries are a priority: Injury data are analyzed and trends in the data inform protocols and other factors that may impact player safety.<sup>49</sup> Second, while the characteristics of game-day shoes used within the league vary, the selection tends to be more informed than it is at lower levels of play. Professional equipment and medical personnel are involved in the selection, and options are informed by annual evaluations of available footwear based on biomechanical testing of traction and flexion behavior.<sup>11,23,27,28,49</sup> Finally, footwear manufacturers are engaged in the process of NFL player shoe fit, and the perceptions of these elite athletes, their equipment staff, and their medical team inform decisions on footwear design.

The development, implementation, and roll-out of a footwear fitting system for use within the NFL is described below. The work, overseen by the NFL Musculoskeletal Committee<sup>49</sup> in collaboration with the NFL Players Association, was divided into 3 phases.

### **Determination of the Foot Scanning Hardware and Quantification of the Population of Interest**

Commercially available foot scanners were identified and evaluated against a set of objective specifications developed in collaboration with the NFL Musculoskeletal Committee and Players Association. For league-wide use to occur, the foot scan hardware needed to be set up within the teams' locker rooms to allow for efficient and accurate foot scanning. Thus, scan time, scanner size, scan resolution, and ease of use were priorities. Ease of use was related to the development level of the software available with each scanner. Further prioritized were the weight and size capacity of the scanner, since NFL players represent an extreme population, and the capacity of the scanner's software to differentiate geometric variation by aspect (right vs left foot). To facilitate that assessment, a player foot scan database was created by scanning 1451 NFL players in NFL locker rooms using several commercially available scanners. The use of aggregated and anonymized scan data was approved by the NFL and the NFL Players Association in furtherance of the research reported here. The NFL regular-season roster is 53 players on each of the 32 teams, so the scanned population

represents a substantial proportion of players. This scanning process therefore generated normative data representing the population of interest and was an opportunity to evaluate the usability of each scanner in the locker room environment with actual players. Anonymized and aggregated scan data are summarized in the Appendix (available online). Foot length and width of NFL players were greater than the general population<sup>18</sup> (Figure A3 and A4 in the Appendix), while more than 50% of players had at least a one-half nominal size difference between their right and left shoes (Figure A5 in the Appendix).

The creation of this foot scan database enabled setup and training of the classification algorithms described below.

### **Determination of a Method to Obtain Internal Shoe Dimensions and Population of a Data Library**

There are multiple methods of quantifying the internal dimensions of the shoe.<sup>24,51,52</sup> Filling the footwear with a dense, radiopaque contrast media and taking 2 radiographic images (side and top view) was used in this project to create a pseudo-3D image of the internal shoe volume and shape, from which selected dimensions were extracted. This method imposes a prestress on the shoe upper (as does a foot), is nondestructive, and compares favorably to dimensions determined from internal shoe casting/molding.<sup>52</sup>

After selection of the internal shoe measurement method, it was necessary to measure size runs of all footwear to be included in the fitting system. Methods were evaluated for scaling dimensions across sizes, and hence reducing the effort required to populate a database of dimensions across full size runs, but no established dimensional scaling methodology could be validated for predicting dimensions of particular models across a range of sizes, indicating that different sizes of a given shoe model do not necessarily have geometric similitude. Thus, all available sizes of every relevant shoe model were acquired, scanned, and measured. This involved scanning hundreds of individual shoes. Past years' and current shoe models were obtained from NFL locker room inventories. Future models were obtained from the shoe manufacturer as they became available. Radiographic scan and dimensional data extraction procedures were performed, and photographs were taken of all shoes. The data and images were indexed to model names and numbers in a digital library. The library is available to all teams via the cloud and is updated as new shoe models become available.

### **Development of an NFL-Specific Shoe-Foot Matching Algorithm**

The initial development of the baseline shoe-foot matching algorithm was first implemented using an extensive database of thousands of scanned feet<sup>25,26,50</sup> combined with subjective comfort assessments for a large number of available footwear models.<sup>51</sup> A proprietary fitting algorithm was employed for this study<sup>25,26,50</sup> and refined to reflect NFL football-specific fit standards developed collaboratively among selected NFL equipment managers, players, and external footwear experts.

NFL players participated in the evaluation and refinement of the algorithm by receiving 3D foot scans and evaluating a set of footwear ranked based on a proprietary fit score. Players completed comfort assessments on a random sample of footwear from the list of recommended footwear, consisting of shoes ranked in the top 30%, shoes ranked in the middle 40%, and shoes ranked in the lower 30% in terms of their fit score, in addition to the footwear they were currently wearing. Players rated the overall comfort, comfort of specific shoe regions (forefoot, midfoot, rearfoot), and used an image of the shoe to highlight areas of tightness and looseness. Forty-three players were scanned, and 15 completed the full survey. Evaluation of the system was determined based on the relative rankings of the fit score assessments compared with the ranking provided by the fitting algorithm. The fitting algorithm was then modified to reflect the player feedback and the expert fitting opinions of the NFL equipment staff and footwear experts.

## DISCUSSION AND FUTURE WORK

Well-designed footwear can improve athletic performance and reduce the risk of certain types of athletic injury, but these benefits may be mitigated by improper fit.<sup>2,35</sup> Thus, properly fitting footwear, especially at the elite level, is paramount. This article provides an overview of the development and implementation of a footwear size recommendation system within the NFL. The system will be available league-wide prior to the start of the 2018-2019 season. Future work will aim to verify and quantify system acceptance, perceived value, and reliability, with an ultimate goal of understanding the influence that placing athletes in properly fitting footwear may have on injury mitigation. Further advancements in the shoe fitting system may also be implemented, such as through the incorporation of plantar pressure measurements, further refinement of the fitting algorithms, and additional technology such as dynamic foot scanning.

Systems functionally similar to that described here have been implemented in some retail settings, but this is the first system to the authors' knowledge developed specifically for a sports league. As with any development and early adoption of technology, significant challenges were identified. A range of acceptable foot scanning hardware is available, but the technical development of the software interface often lags, and some hardware providers lack the capacity to distribute and support their systems. The state of shoe libraries, shoe measurement methods, and fitting algorithms lags even further. Furthermore, these methods are often closely held intellectual property, which can preclude the open and transparent assessment of their validity. At the start of this program, there were no broadly accepted and validated methods for quantifying the interior shape of an American football shoe or for geometrically matching foot shape to shoe shape for the unique case of American football. Thus, the program described here is considered the first step in a process toward a validated, broadly accepted methodology and system. Additional work is

needed before the fitting algorithm and other methods described here can be considered fully validated.

The near-constant redesign of athletic footwear and introduction of dozens of new models each year poses a significant challenge to the maintenance of a library of shoe dimensions. While multiple models across years may be manufactured on lasts of the same shape, it is currently not possible to identify models and years that are sufficiently similar geometrically and for which the measured values may be considered identical for the purposes of the shoe library. Such information would significantly reduce the effort required to maintain the shoe library by limiting the number of models that would need to be measured each year. Efforts are ongoing to engage footwear manufacturers in this process.

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